Master's Thesis

Terahertz detector with aperture for enhanced performance and resolution by near-field microscopy technology

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Abstract
Imaging technology in sub-THz frequency range (f= 0.1~1 THz) has various applications such as scanning the body in security and medical region.

Recently, some research group have been reported on the multipixel THz detector for real-time and large-area THz imaging [1,2]. However, since sub-THz waves have relatively long wavelength (λ= 0.3~3 mm), and it cause the limit of spatial resolution in THz imaging by its diffraction limit (λ/2). In this work, we experimentally demonstrate the enhanced photoresponse and spatial resolution of THz detector with novel nano-scale aperture by near-field microscopy technology.

The layout of FET with aperture width of 1 μm and probe distance of 280 nm, which is designed in single copper layer for enhancing and focusing the electric field when THz wave is incoming. Through the raster scanning of key-shape structure at 0.5 THz, the photoresponse of detector with probe-type aperture is 7 times more enhanced than without aperture. Furthermore, the spatial resolution, which is minimum distinguishable distance between boundary of materials, of detector with aperture is 2 times higher than detector without aperture. Therefore, our probe-type aperture design on THz detector can provide the possibility of high performance and resolution THz imaging system.

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Nomenclature and Predicate

2DEG	Two-dimensional electron gas
Ac	Alternating current
CMOS	Complementary metal-oxide semiconductor
dc	Direct current
FET	Field-effect transistor
FPA	Focal plane array
HEMT	High-electron-mobility transistor
HFSS	High Frequency electromagnetic field simulation software
IC	Integrated circuit
MOS	Metal-oxide-semiconductor
NEP	Noise equivalent power
NMOS	N-channel metal oxide semiconductor
OAP	Off-axis paraboloidal
PCB	Plastic chip board
R_v	Responsivity
RF	Radio frequency
Si	Silicon
THz	Terahertz
UNIST	Ulsan national institute of science and technology
VNA	Vector network analyzer

Introduction

1.1 THz technology

The wave that has terahertz(THz) frequency range (f= 0.1~10 THz) is formed between electronics and optics. The wave has unique property that are harmless, permeability and straightness [3]. By those property, the wave has big potential in various application. The antenna design and complex metal oxide semiconductor (CMOS) sensor are developed by the electronics. The near field microscopy and photo detector are researched by the optics, which is described in figure 1.

Imaging technology is more promising and attractive in near-future, non-destructive human body inspection, security, and biomedical applications rather than other technologies [4-7]. For example, mm-wave scanner is well using in airport nowadays. Specially, terahertz wave has used in inspection equipment for checking the defect of MOSFET. Recently increasing of degree of integrate and decrease the gate length, aspect ratio is increase. Therefore, the equipment is needed to increase the yield of MOSFET chip. Two equipment is in figure 1-2.

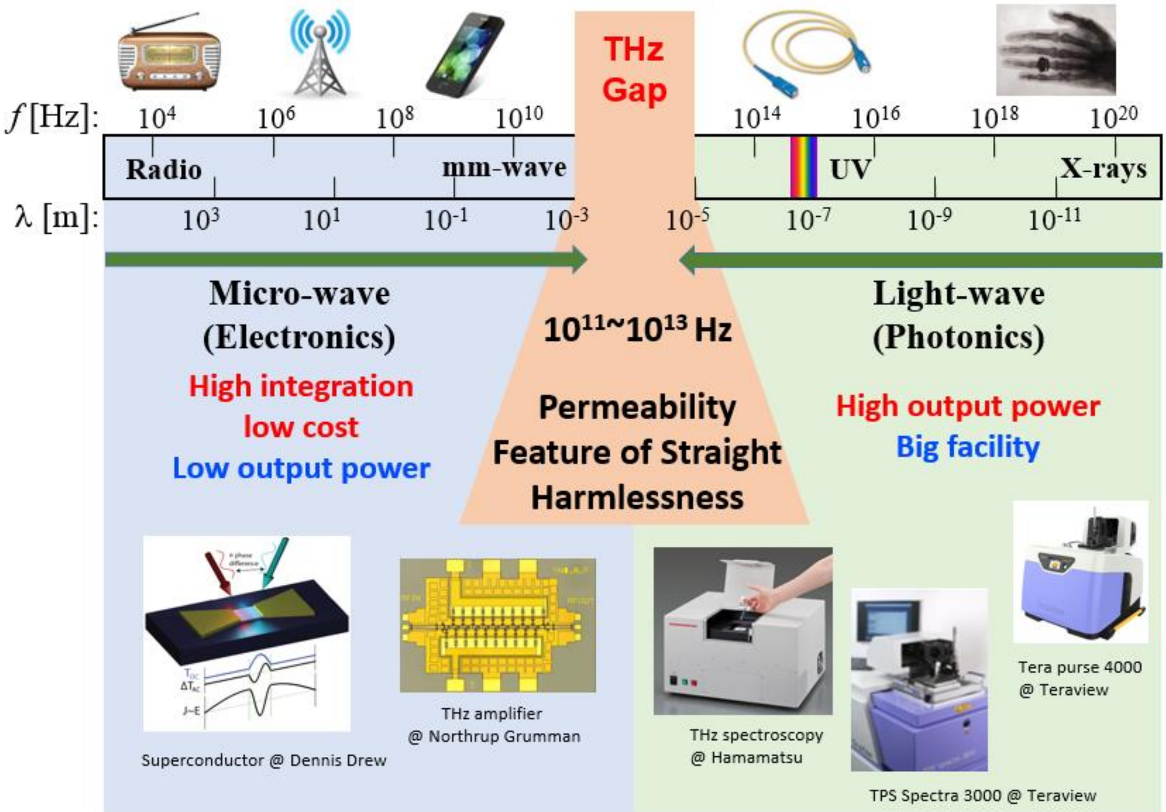

Figure 1-1. The spectrum of the electromagnetic waves

1.2 Plasmonic detector

The detector is usually act as transit mode and the limit of gate length almost 10nm, so the limit of acting frequency is under 1THz. However, MOSFET can reacted over 1THz at plasmonic mode. The compound semiconductor's operating frequency is higher than plasmonic detector as in figure 1-3 [8]. However, the price of high electron mobility transistor is higher than field effect transistor based on silicon.

Plasma wave transistor (PWT) is described with two-dimensional electron gas (2DEG) which is gathered by gate overdrive voltage. Group of electrons goes through the channel with plasma wave velocity that is much higher than the local electron velocity.

Plasma wave transistors (PWTs) based on field-effect transistor (FET) have been proposed for the terahertz (THz) wave detector. In the channel with two-dimensional electron gas (2DEG), electrons flow with plasma wave velocity which is much higher than the local electron velocity. PWTs have two different regimes of non-resonant and resonant operation. In case of detector, resonant detector can provide the maximum responsivity in the resonant condition with underdamped plasma wave through the channel when the plasma wave forms a standing wave.

Figure 1-2. Application of THz frequency

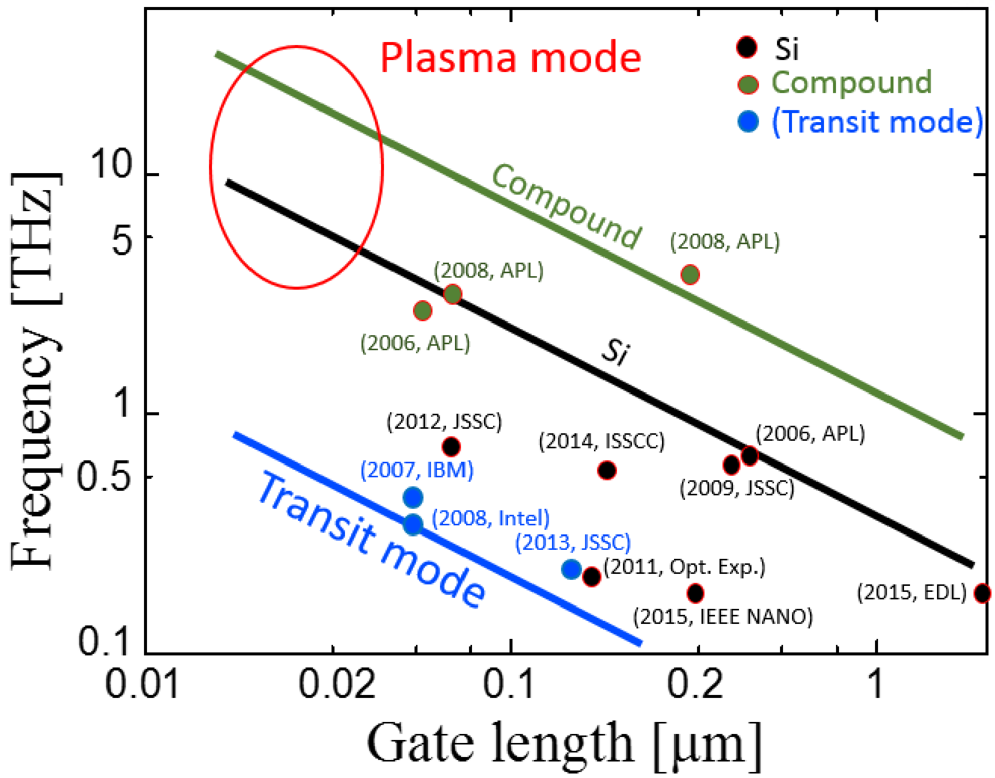

Figure 1-3. Operation frequency by gate length change

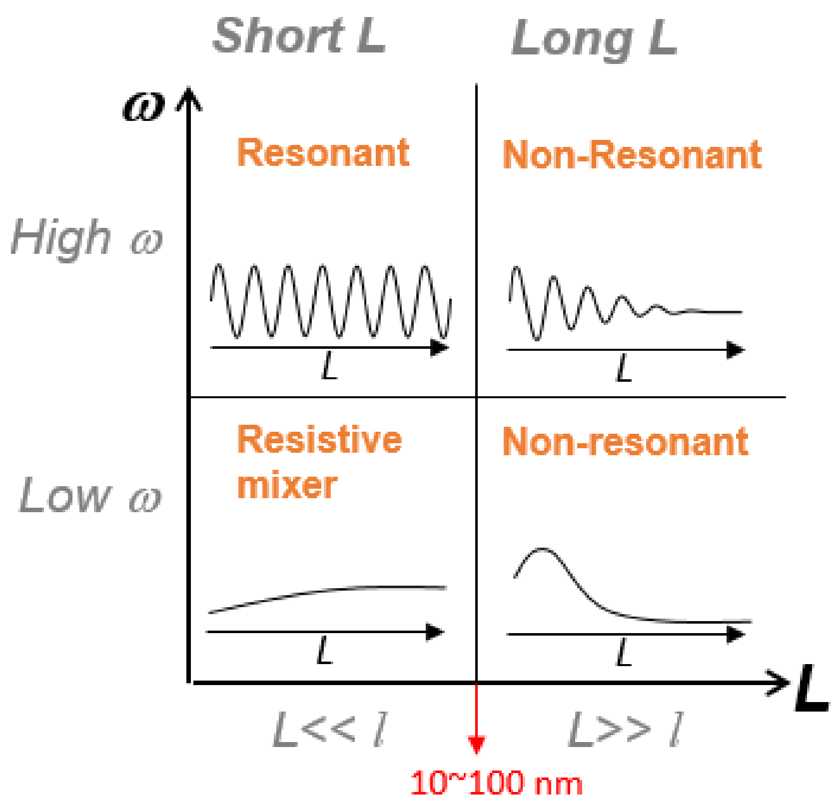

Figure 1-4. Four type of plasmonic detection mechanism

1.3 4 operation mechanism of plasmonic detector

ω is frequency of input wave, and the mode is divided by two part. One is high frequency regime, the other is low frequency regime as like figure1-4, 1-5.

The high frequency regime has two mechanism short gate(L< sτ) and long gate(L>>sτ). The short gate case is act as resonant mode. The plasma wave can reach from source to drain. In silicon case, the gate length should be shorter than 10nm. The long gate case, the plasma wave cannot reach from source to drain [9].

The low frequency regime has two mechanism that same to high frequency regime. However, the plasma wave cannot exist owing to an overdamping. Therefore, short gate case operation as resistive mixer and long gate case operation as non-resonant mode.

Characteristic length l

Low frequency: $\omega\tau << 1 \qquad l = s(\tau / \omega)^{1/2}$

High frequency: $\omega\tau >> 1 \qquad l = s\,\tau$

Where τ **(momentum relaxation time)** $= \mu \cdot m_e^* / q$

s **(plasma wave velocity)** $= \sqrt{eU_0 / m_e^*}$

Figure 1-5. parameter for plasmonic detector

1.4 Non-resonant mode

Non-resonant mode caused by low mobility of plasmonic THz detectors which is Si based MOSFETs. Non-resonant operate can react by THz frequency wave by source to drain voltage difference between in sub-threshold conduction channel. As shown in figure 1-6, when the channel inversion layer is not strongly formed in a weak-inversion regime by biasing dc gate voltage below threshold voltage, incoming THz wave, which can be modeled as the ac signal with a frequency, induces the channel 2DEG oscillation with the propagation length. Under the asymmetric boundary conditions by the external gate to source and gate to drain impedance, dc drain to source output voltage can be obtained from the time-averaged asymmetric channel charge distribution.

For increasing the dc drain to source output voltage, asymmetry ratio should be increase. The method that increasing the asymmetry ratio is make capacitance asymmetry by asymmetry of structure. For example, increase the overlap area that only at drain side, then capacitance of gate to drain and gate to source has asymmetry condition.

To estimate performance level of THz detector, we should know two standard performance metrics, responsivity and noise equivalent power. Responsivity is output voltage by unit input power and NEP is defined by minimum detectable power against detector noise.

So, higher responsivity and lower NEP gives better detector performance. The reported detectors generally have output voltage under the level of milli-volt, thereby, amplifier stage should be needed about 40 dB gain, so multi-pixel detector as shown in previous slide has limit of demonstration.

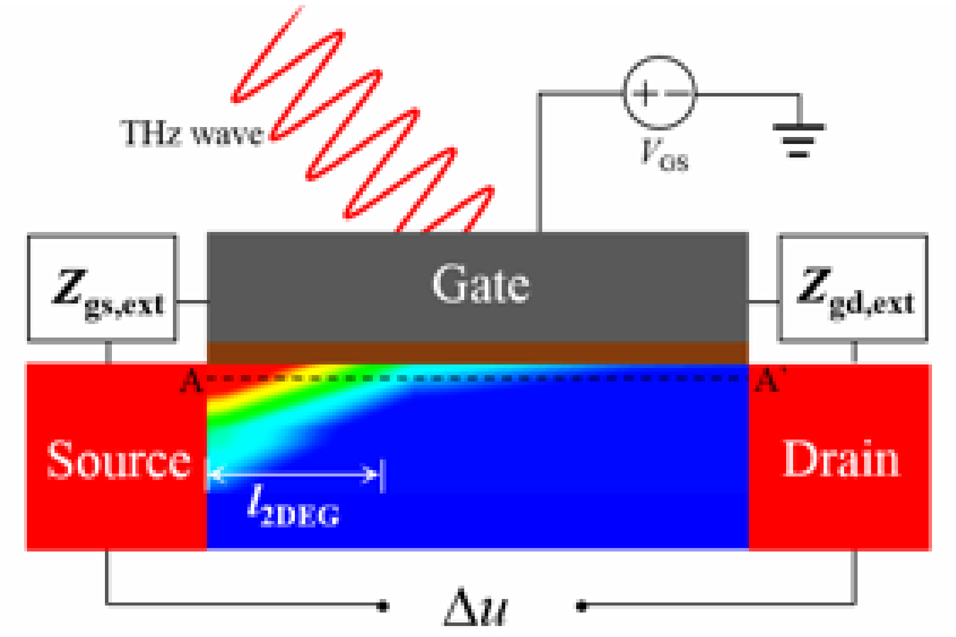

Figure 1-6. Detection mechanism of non-resonance plasmonic detector

1.5 Motivation

By asymmetric condition of non-resonant mode electric field can be effect on gate that toward to source region. The electric field is enhanced by ac voltage that biased in gate, and the ac voltage is captured by antenna. Therefore, the resolution is defined as wave length and the antenna size is almost 0.1 to 1 mm. That design has low spatial resolution and big pixel size, as it shown Figure 1-7(a)

The asymmetric condition is same as previous design. The ac voltage that biased in gate is induced by near field induced by probe. The near field that induced by probe is evanescent wave, so the power of wave is exponentially decrease. The probe should be closed to gate and it can enhance the spatial resolution. The size of probe is 1 to 10μm that is much smaller than antenna. Therefore, new design has high spatial resolution and small pixel size, as shown figure 1-7(b).

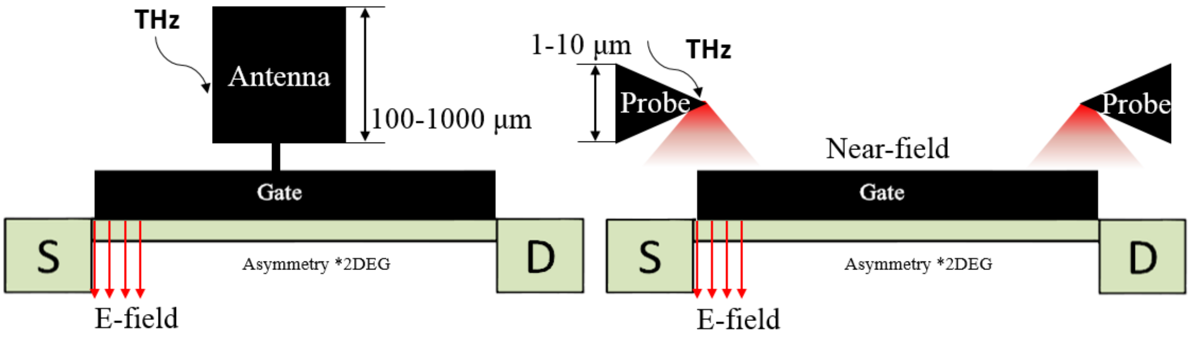

Figure 1-7. Schematic antenna with detector and near-field probe with detector

Analysis and simulation

2.1 Near field microscopy technology

The electric field is divided to two field by diffraction. The far field follows Huygens's principle and the wave is almost plane wave. The near field follows Fresnel diffraction and the wave is almost spherical wave [10].

If the slit size is very smaller than wave length, the most of wave is reflected to slit. The evanescent wave generated after passing surface of silt, it is one of the near-field. The evanescent wave is exponentially decreased, so the wave no effect to far side. In figure2-1, even if the delta x is smaller than wavelength, wave can scatter to only red particle. By using that effect the resolution is enhanced by near field microscopy technology.

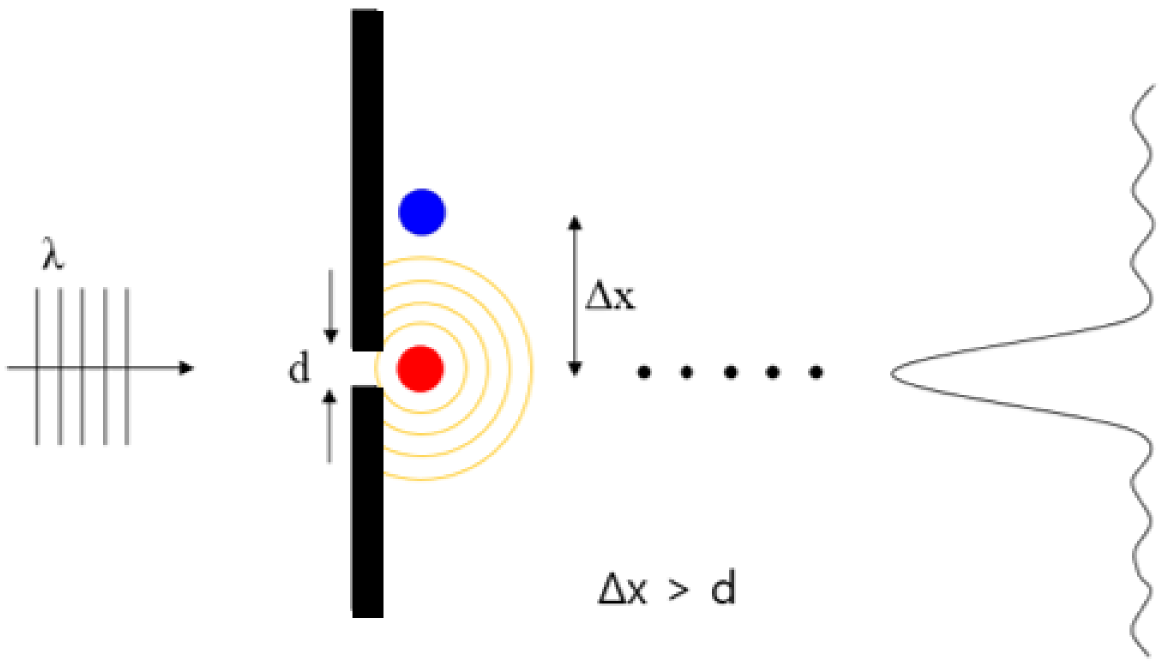

Figure 2-1. Near-field detection principle

2.2 Two method of near field microscopy

The main point of near field microscopy is how to makes the near-field wave. In figure 2-2, we have two big method. The one method is aperture that diameter is smaller than wavelength. The other method is probe tip that edge is smaller than wavelength [11]. These methods are mostly used in near field microscopy area.

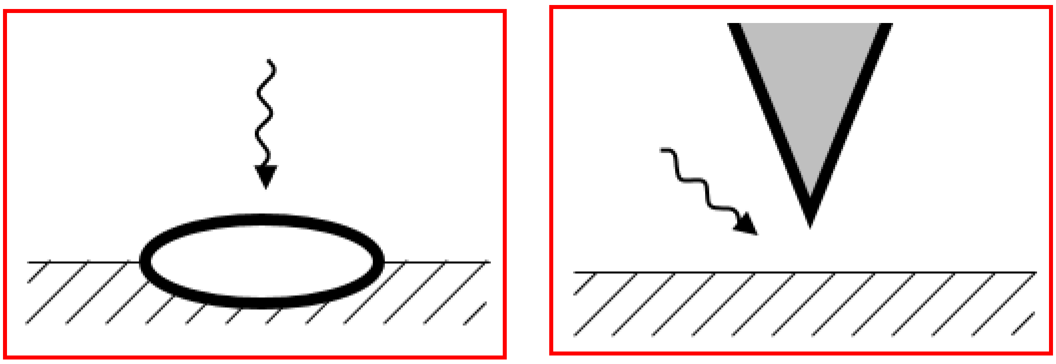

Figure 2-2. near field excitation method (aperture, probe)

Aperture type

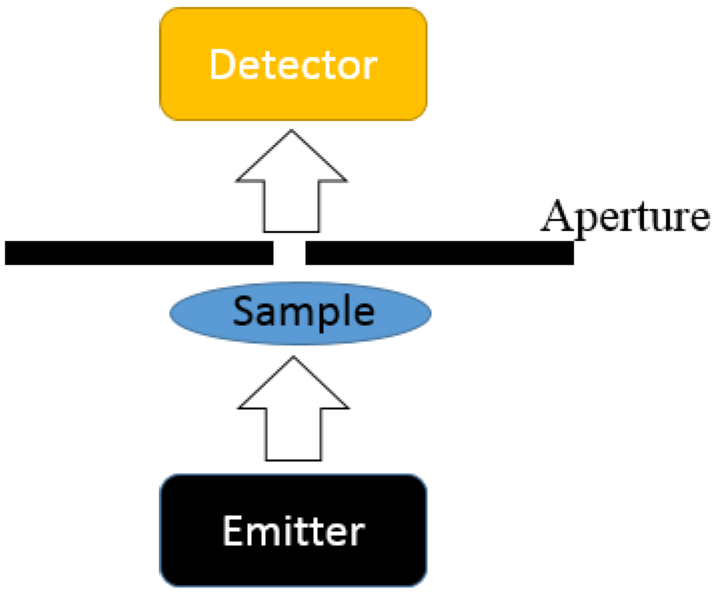

Figure 2-3. System of detection using aperture type detector

The simplest way to making near-field is aperture. The near-field power is decrease by aperture size decrease.

In figure 2-3, emitter emit the THz wave it hit the object and distance between sample and aperture is close we can detect the wave that coming out by scattering to sample. If we change the position of sample and detector, emitter emit the wave and passing the aperture, then near-field wave occurs and the sample that surround of aperture is scattered.

The advantage of aperture type is easy to make on-chip design and array structure, so it is proper to real time imaging. However, the power is decrease rapidly by decreasing the aperture size. Therefore, it is relatively small spatial resolution than probe type near-field microscopy.

Probe type

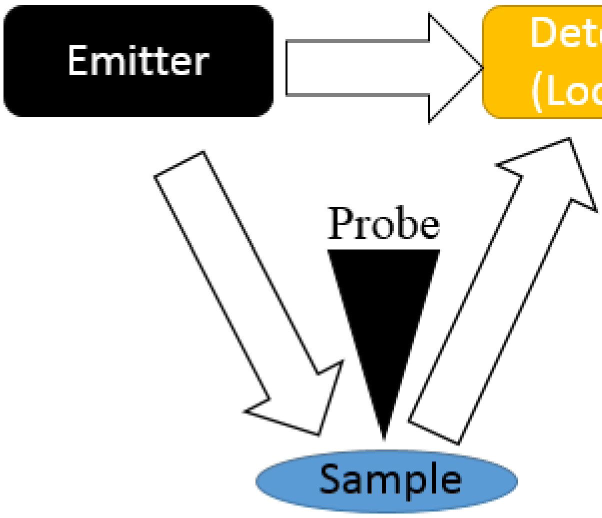

Figure 2-4. System of detection using probe type detector

The probe type near-field microscopy is using scatter to probe tip. By that scattering near-field wave is occurred and detect the sample, as shown in figure 2-4.

Differently to aperture type, probe type needs to lock in mechanism. Because of unexpected scattering to sample of other direction.

The advantage of probe type is high spatial resolution. The resolution of probe type is same as edge of probe, so it can be much smaller than aperture type. However, the optical system is needed by lock in mechanism, and it is hard to make array structure. So, it is not proper to real time imaging system.

2.3 Simulation by using HFSS simulation

In figure 2-5, the waveguide that diameter is D, and the distance from edge of waveguide is x. The boundary between far-field and near-field is $2D^2/\lambda$ [11]. Therefore, around that point electrical field is exponentially decrease, and around the wavelength electrical field is decreased by linear. For increasing the boundary, increasing waveguide diameter and decrease the wavelength. It is well matched to theorical result and simulation result.

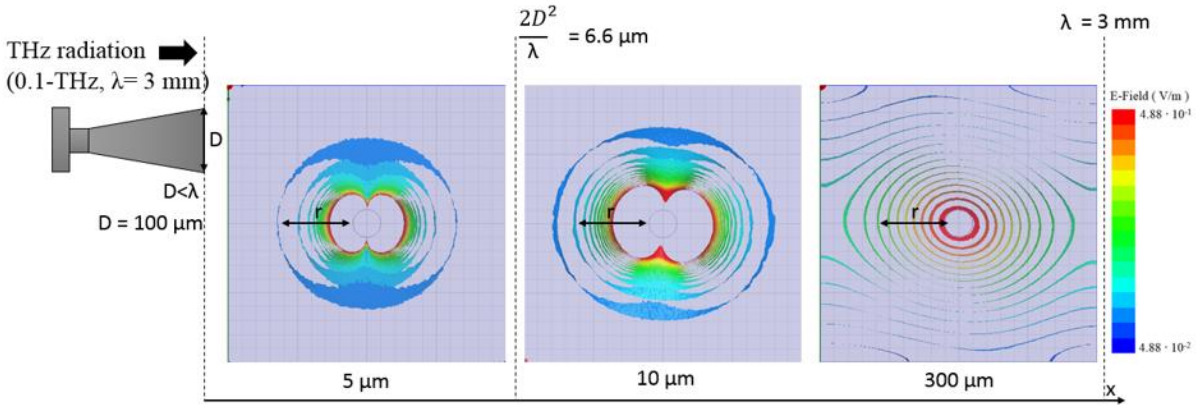

Figure 2-5. Simulation for confirm the near field

2.4 Enhancing the E-field by probe tip

We look about the two method of near field microscopy in section 2.2. The aperture type is proper to array structure, because of it can make on-chip design. However, the intensity of near field is decrease by aperture size decreased. Therefore, we should enhance the near field, and the solution is using probe tip that role of making another near field.

Then we make the aperture with probe design in single layer. We expect the enhancing the near field. For checking the field enhancing, we using HFSS program that can check the distribution of electric field.

The near-field microscopy that aperture type is decrease by rapidly by decreasing the hole size. For enhancing the electrical distribution, using the probe that same layer to aperture. Only changing of shape of aperture, it effected to field enhancing.

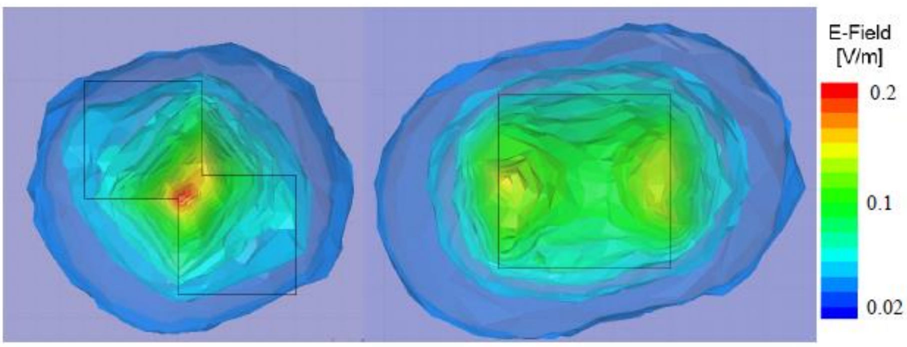

Figure 2-6. E-field distribution of aperture with probe and only aperture

2.5 Antenna simulation

The s parameter is coefficient that division of voltage and power in 2-port network. S11 parameter is reflection coefficient, so small S11 parameter means high antenna efficient.

The upper graph of figure 2-7 is simulation of only substrate that didn't have device and metal pad, so there is only absorption by substrate. The below graph of figure 2-7 is simulation of device and metal pad.

Two graphs are almost same, then we know pad and device is does not much effect at antenna simulation. The near-field wave is excited at aperture of probe, but it is decrease rapidly, so it cannot effect on antenna port. Therefore, it is correct result in simulation.

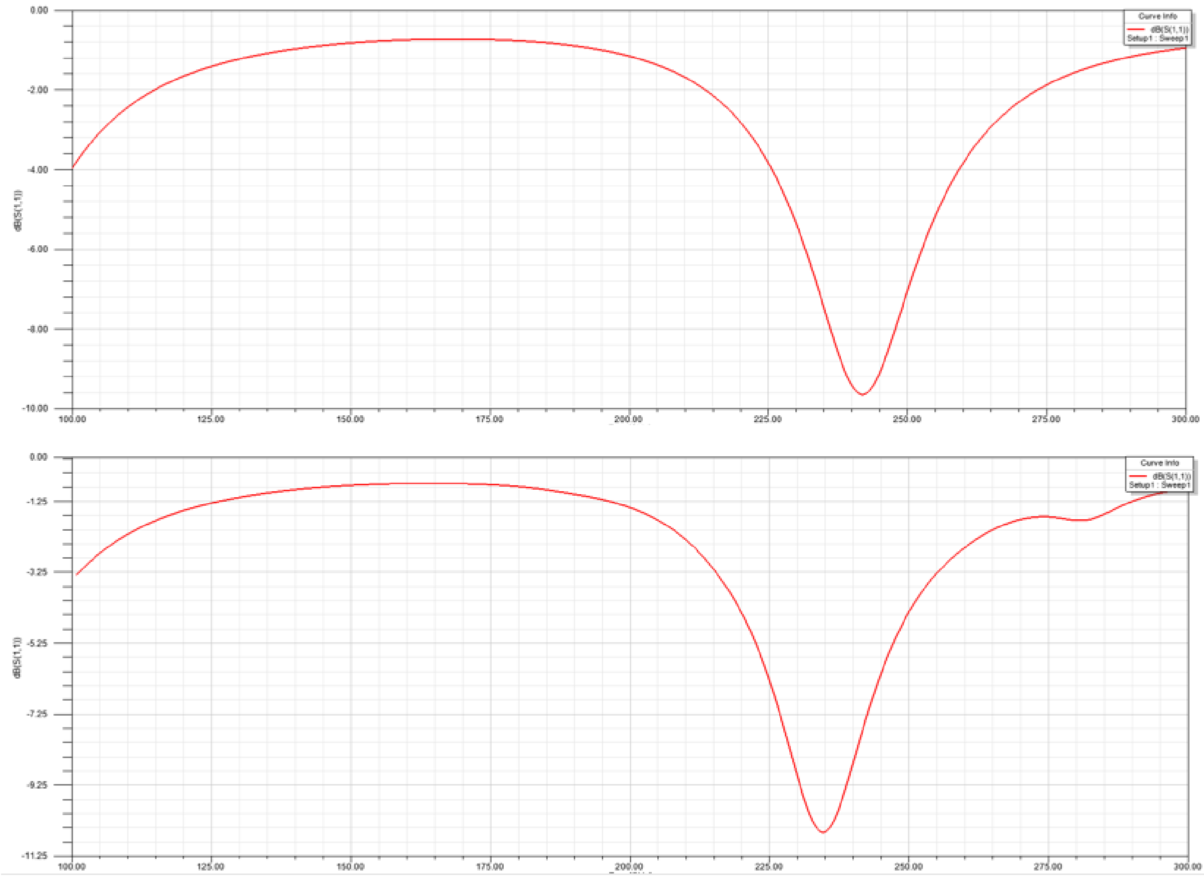

Figure 2-7. S11 parameter for substrate and device with metal pad

Experiment method

3.1 Layer design and cross-section view of device

The device design is based on MOSFET structure and making near field probe and aperture by upper metal. Figure 3-1(a) is mask design of Samsung and SK Hynix foundry process. The green part is gate poly and gate oxide, red area is aperture and probe and yellow area is doping area that source and drain region.

Figure 3-2 is chip on board design, the center area is detector region and the detectors are connected to board by metal wire. The aperture is made by cupper that upper layer of poly gate layer, the gate is made by poly silicon for self-align process.

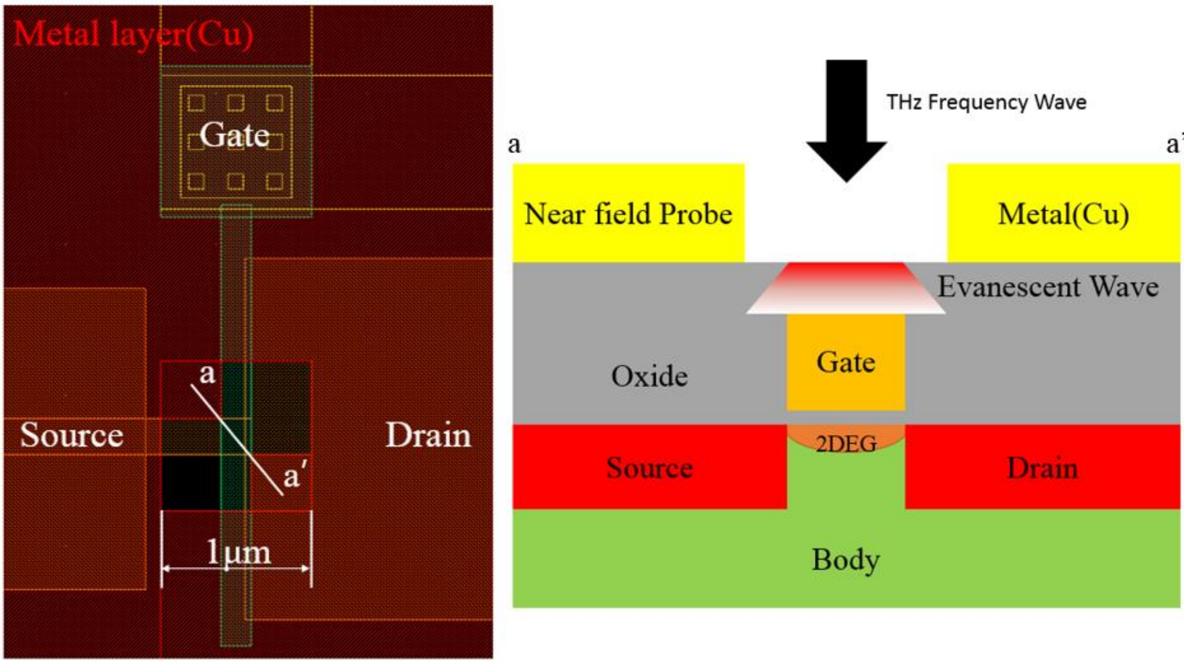

Figure 3-1. Top view and cross-section view of near-field detector

Figure 3-2. picture of real chip on board system

3.2 Experiment setup

There are two experiment structure, one is figure 3-3 (a) the other is figure 3-3(b). The THz emitter is gun diode that emit the 100GHz to 500 GHz frequency, as shown in figure 3-4.

The upper picture is structure for confirmation of near field and under picture is structure for imaging system. The OAP mirror is for focusing THz wave, it is enhancing the intensity of THz wave. In figure 3-3 (b), aperture and detector are designed in one chip, so the distance between aperture and detector is smaller than 1μm.

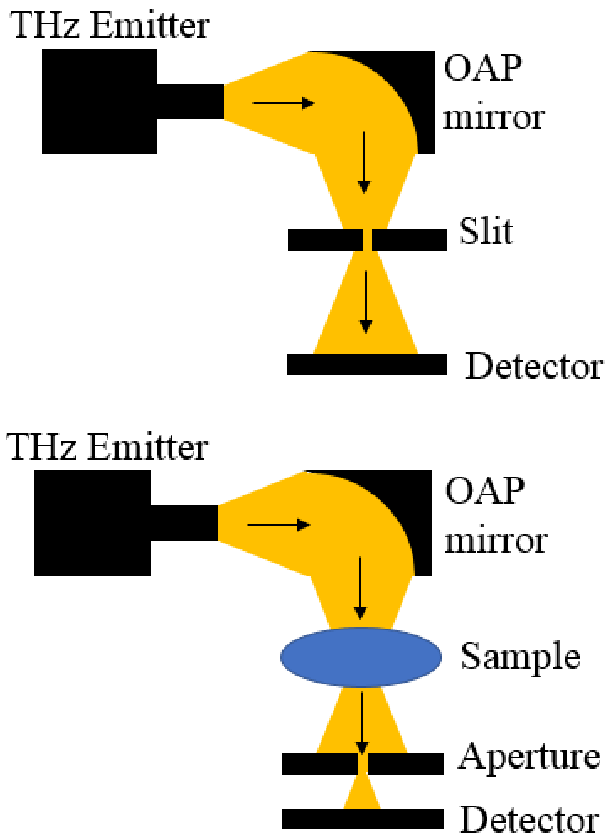

Figure 3-3. Imaging system structure for slit and sample detection

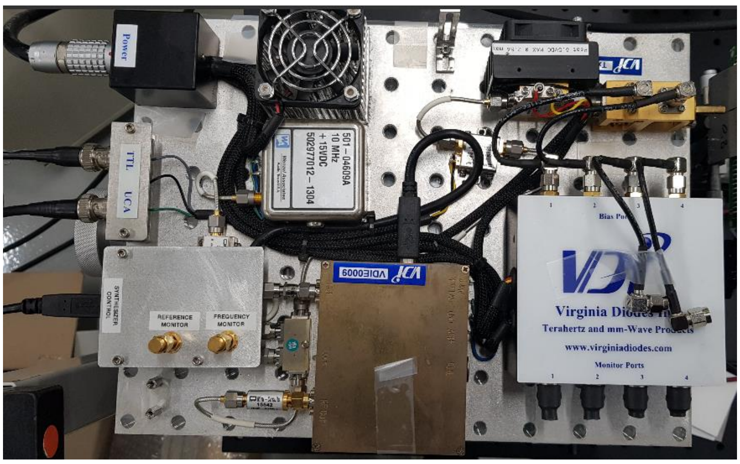

Figure 3-4. Real picture of Gun diode

Results

4.1 Confirmation the near-field by experiment

The wave that passing the aperture is evanescent wave, so the power of wave is exponentially decrease by increase the distance from the slit. After boundary of near-field and far-field, the wave is changing to far-field wave, so the wave doesn't decrease same order to near field.

The frequency of incident wave is 120GHz. And it has almost 3mm wavelength. The aperture is made by aluminum and the thickness is 100μm. The thickness aperture should be smaller than aperture size, because of evanescent wave is usually extinction by after aperture size.

In this experiment the regions of exponential decreasing are 660,460,360μm by each aperture size 1.0, 0.9 and 0.8mm. The values are almost same as calculation in section 2.3.

This method is one of the confirm that the near-field wave occurred in new design.

If we have very small aperture, the boundary of far field to near field is very small. Therefore, we should have short distance between aperture to boundary.

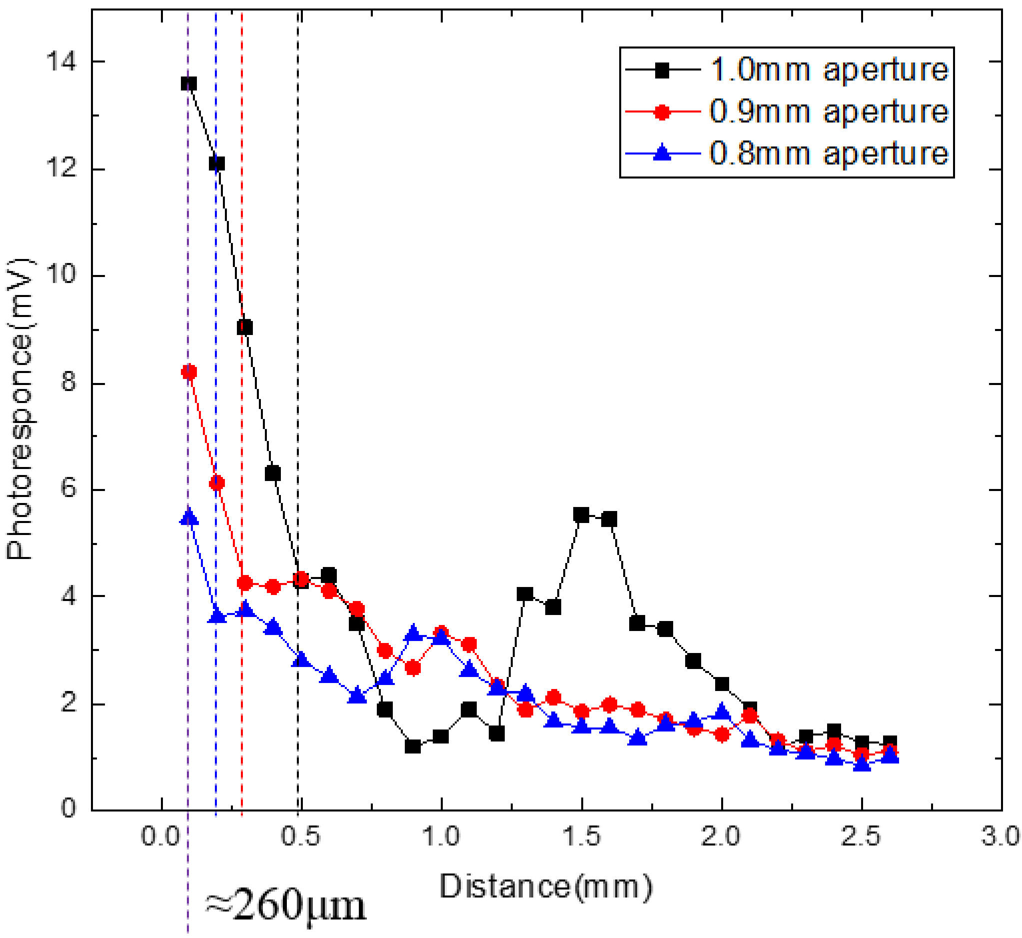

Figure 4-1. Photo response change by distance from slit to detector

4.2 Imaging of key shape hole

In this experiment, one detector is designed at figure 3-1, the other detector is designed at figure 1-7. First detector and second detector have same MOSFET detector, but first detector have near-field antenna and second detector have electrical antenna.

The sample shape is looks like at figure 4-2. The detection mechanism is scanning the sample by 250μm step size. The scanning area is 5x4 cm region.

The results in figure 4-2, we can see the enhancing of resolution by near-field antenna. Specially, the rough region that right side of key shape hole.

More detail of the result that figure 4-3, it is value of b to b'. The photo response of near-field antenna with detector is 7 times bigger than electrical antenna with detector. By that result, if the distance between near-field antenna and detector is closed the photo response can be high than electrical antenna.

For measuring the resolution of two detectors, normalize each photo response and comparing the distance between 80% to 20% of local maximum value. The resolution is 2 times enhanced at figure 4-3.

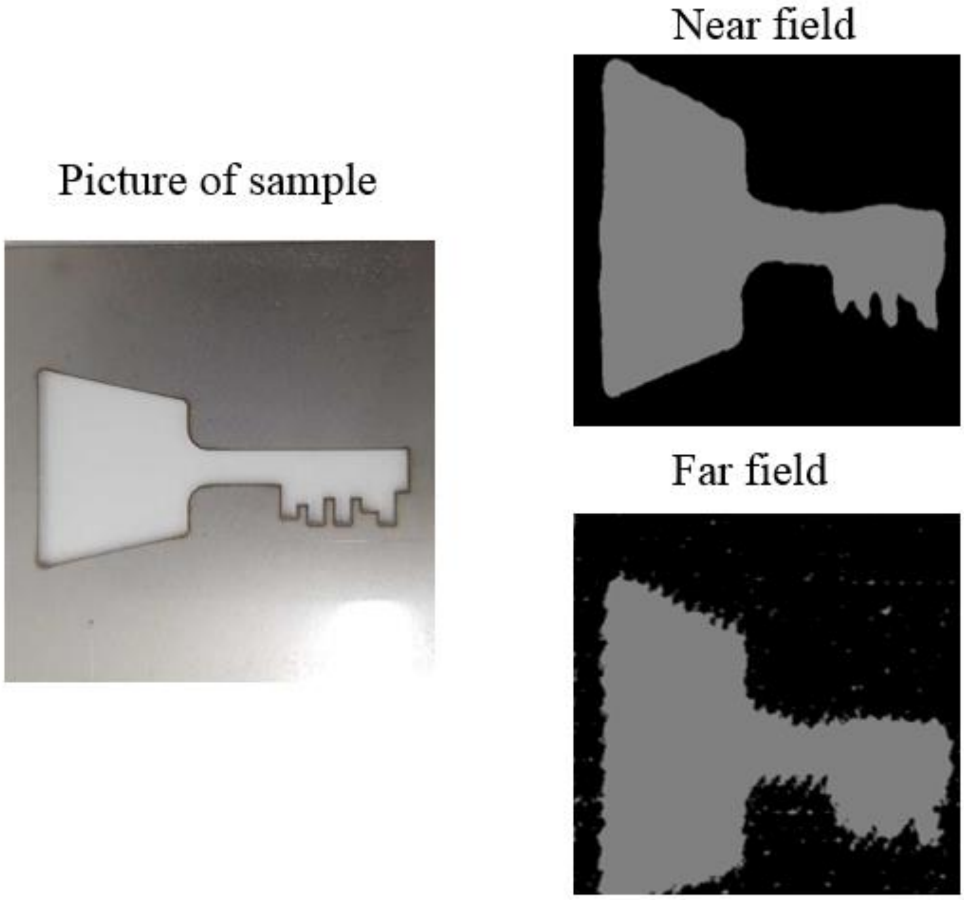

Figure 4-2. Scanning image of key shape slit(real picture, near-field antenna, far-field antenna)

The imaging system for this new detector is almost same as near field microscopy. The point of imaging system is the position of near field source and the position of object and the distance between source and object.

In case of classical method of near field microscopy that has aperture, the near field occurs after passing aperture. And the near field scatter the object, the transmittance wave is detected in THz detector.

On the other hands, the new design of detector case also has aperture. The THz wave is scatter to object and the transmittance wave is incident wave of aperture. The incident wave is also evanescent wave, so the new detector is detecting the that wave. Therefore, for enhancing the resolution of imaging system. We need the high spatial resolution detector and distance between object and detector should be small.

The new designed detector has more high spatial resolution. However, the distance between object and detector is limited to almost 200μm same as section 4.1. If we can decrease the distance between object and aperture, we can enhance the resolution of imaging system more than this work in figure 4-3.

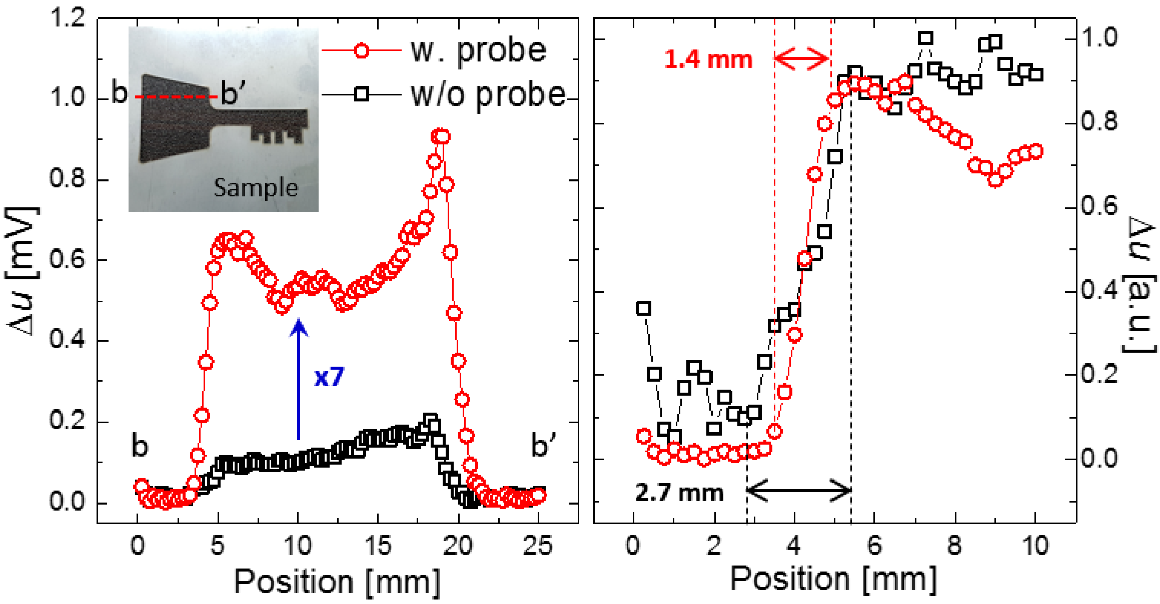

Figure 4-3. Data of imaging of key shape slit

Summary

A high resolution plasmonic THz detector have been experimentally demonstrated by using near-field microscopy technology. When the aperture diameter (1~2μm) smaller than wavelength (1.5mm), Power is rapidly decrease. For prevent power loss, we design the new aperture design. By E-field distribution and Maximum magnitude of E-field, we prove the aperture with probe have high field and small spatial resolution. The aperture with probe has 7 times E-field enhancement and 2 times spatial resolution enhancing, just changing simple aperture design

Further work

By using the Confirm the near-field by experiment at section 4.1, we can check the evanescent wave in foundry process. Decreasing of the distance between near field probe and detector as figure 6-1, the photo response is exponentially increase by figure 6-2, if the evanescent wave occurred.

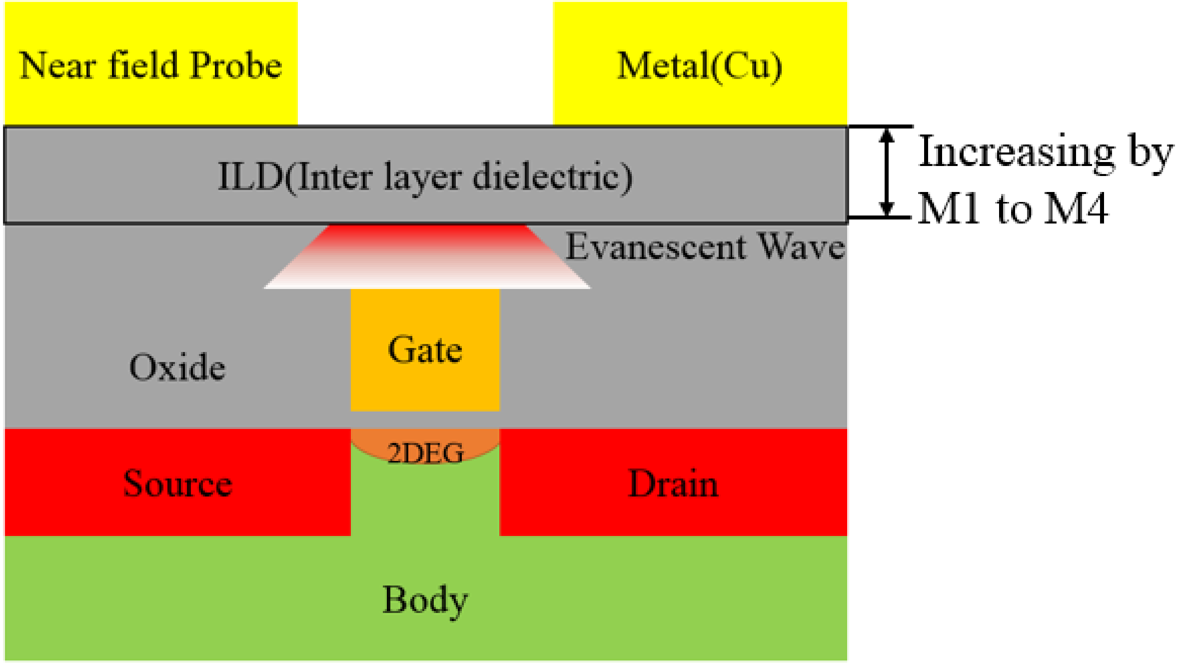

Figure 6-1. Structure for confirm the near-field using on-chip design

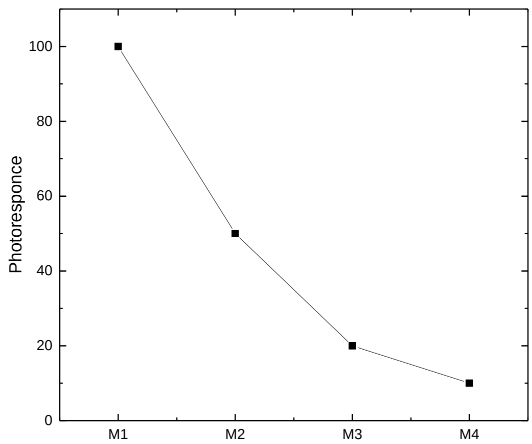

Figure 6-2. Expected result of confirm of near-field

New aperture design for near-field Terahertz imaging system is suggested with more enhanced and focused E-field based gate act as near field probe. And the channel is formed as graphene, as shown in figure 6-3.

We expect the enhancing the near-field distribution by decreasing of distance between near-field antenna and detector. And this structure is purely probe type that doesn't have aperture, so we expect enhancing the power density and spatial resolution more.

The graphene should be existed in the channel region, so the process is more complexed than previous work. However, for real time scanning this technology is needed.

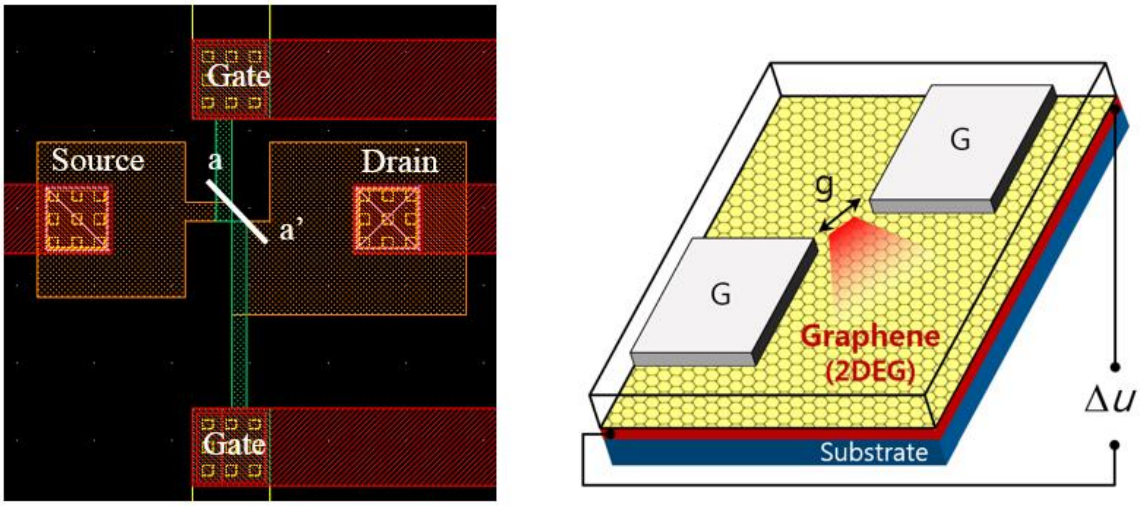

Figure 6-3. Top view and cross-section view of apertureless design

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